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15535 U.S. PTO
60/528169
120903

PROVISIONAL APPLICATION

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Case: 8-3-4

Title: An IEEE 802.11a Compatible Training For Multiple Antenna OFDM Systems

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PROVISIONAL APPLICATION COVER SHEET

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This is a request to file a Provisional Application under 37 CFR 1.53 (c).

[X] [30] pages in Specification
[ ] [ ] sheet(s) of Drawing(s)
[ ] The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.
[ ] The name of the U.S. Government agency and the Government contract number are:

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Respectfully,

Date: 12/9/03

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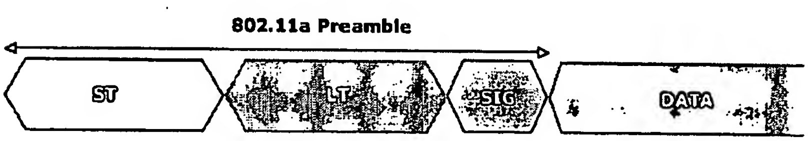
Statement of problem solved by the invention

Problem

A system according to the IEEE 802.11a or g Wireless LAN standards [1][2] uses OFDM as one of the modulation schemes. The system consists of a transmitter (TX), generating the source baseband signal that is modulated in the digital domain and after digital-to-analog conversion, is upconverted to RF frequencies in the analog domain. After passing a channel, that signal is input to a receiver (RX), starting with an analog RF section, which filters out the wanted frequency band and downconverts the signal to a baseband signal. The baseband signal is demodulated in the digital domain to data bitstream again. Part of the OFDM demodulation is the estimation of the channel transfer function and synchronization by means of the training symbols available in the preamble of IEEE 802.11a and g frames.

A future development within the IEEE TGn workgroup is a MIMO (multiple-input, multiple-output) system, based on the OFDM modulation as described above, but with two or more TX sources and two or more RX, communicating in the same frequency band. Taking adavantage of the progation channel properties, the datastreams can be seperated. Not certain, but likely wanted is backwards compatibility with the OFDM modes of IEEE 802.11a and g. The current OFDM preamble and SIGNAL field is shown in Figure 1. The SIGNAL field and SERVICE field – the first 16 bits of the DATA – makes the PLCP header. For backwards compatibility, it is sufficient that legacy devices recognize the preamble and SIGNAL field of the new TGn devices, so they can defer for the duration of the packet.



ST = Short training (10x)
160 samples
LT = Long training (2.5x)
160 samples
SIG = Signal field
80 samples

Figure 1 – IEEE 802.11a and g OFDM Preamble.

The legacy preamble of Figure 1 contains two long training (LT) symbols plus guard interval (GI), currently coming from a single antenna (or an entity that behaves like a single antenna). For future TGn or MIMO devices it is necessary to have a certain LT symbol available for each TX antenna. Hence, the problem is to construct a MIMO preamble and SIGNAL field that is backwards compatible with 11a and g and in the mean time provide channel information, i.e. training symbols, of each of the TX antenna that is orthogonal to the other TX antennas.

New solution

This part considers the 2x*M* MIMO case only, with two TX antennas and *M* RX antennas (irrelevant to the new solution). The description of the invention provides expansion to more TX antennas. The new solution keeps the legacy preamble and SIGNAL field intact by transmitting this part at both TX antennas simultaneously. After this preamble and SIGNAL field the new training symbols are transmitted, see Figure 2.

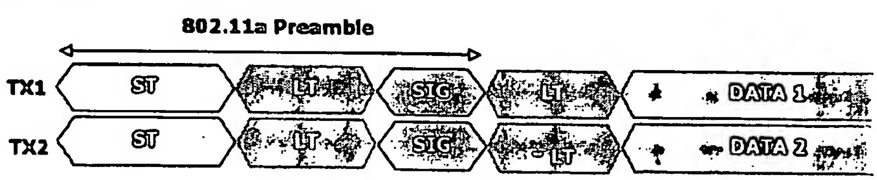


Figure 2 - MIMO preamble with time-orthogonal LT symbols, compatibe with legacy devices.

The new training symbols are identical to the IEEE 802.11a LT symbols – i.e. 1.6 μs guard space and two times 3.2 μs IEEE long training data – except for the polarity of one TX antenna. TX2 transmits these LT symbols the second time with reversed polarity, i.e. multiplied by -1. With simple digital processing the channel transfer function for each TX antenna can be obtained at each of the *M* receivers. Furthermore, tasks like frequency synchronization and symbol timing are enabled by this design.

A straightforward method to get separated LT symbols for each TX antenna, is to transmit them separately, similar to Figure 3 [3]. The advantage is that the LT information per antenna is available without further processing, with similar performance compared to the legacy devices. To compensate power, the LT and SIG fields may be transmitted 3 dB higher compared to the ST. The disadvantage is the variation in power, even without the temporary increase of 3 dB. Where the receiver will likely be able to handle this sufficiently to just receive the SIG field (enough for compatibility), the transmitter will have a hard time to keep the power constant, being an issue for MIMO. The most dominant effect is called power-droop, an effect that relates to turning on and off the power amplifier stage (PA) of the transmitter and shows as a decay of the output power over time. Another effect is VCO kick. An on-chip oscillator (VCO) will get distorted by turning on and off the PA. It will slowly return to its stable oscillator frequency. If these effects appear in the ST fields, the effect may have died out sufficiently to get good performance. If these effects will appear in the middle frame, at the start of the LT or DATA field, the whole frame will be corrupted without additional measures in the RX. This will be very hard to put in standardization. An additional drawback of the time separated LT symbols is the less energy available for the training and synchronization process. If this is compensated by 3 dB higher transmit power (inherently resulting in less efficient PAs: disadvantage), the AGC may not correctly set. Since the AGC sets to the combined power of the STs, it might (soft) clip when there is large difference in received power of each TX antenna. This results in performance loss in MIMO mode. Likely the legacy devices are robust enough to deal with this slight increase, since the SIG field is sent at the most robust rate (BPSK modulation, coding rate ½).

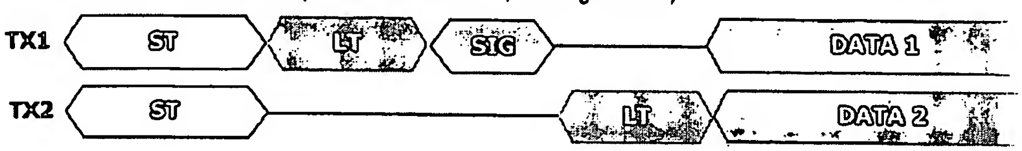


Figure 3 – MIMO preamble with repetitive LT symbols, compatibe with legacy devices.

Other solutions try to combine LT symbols within the normal LT field. Each TX antenna transmits part of the total LT signal and that part is orthogonal to the part(s) of the other TX antenna(s). The combined parts resemble a normal LT symbol and could be detected by legacy devices as normal training symbols. At the MIMO receiver side, the received LT symbol is separated in the orthogonal parts again and used to estimate the channel over the whole band (e.g. by interpolation). An example of such a solution is called diagonally loaded training symbols and is described in an IDR before [4] as well as in literature [5, IV-C]. The channel per TX antenna is estimated in the frequency domain by interpolating the values between every other subcarrier. A possible issue is the backwards compatibility if the channel estimation is done in the time-domain, instead of the regular frequency domain. Besides that, it results in irregular distributed estimation errors and therefore in less performance.

Also the basic orthogonal structure for the new solution is already known. In [5] is described how a MIMO training sequence is constructed with a basic training symbol and an orthogonal space-time matrix. The family of "pilots", as they call it, is the set of Orthogonal Space-Time Pilots Matrices (OSTPM). The new solution specifically adds the backwards compatibility to that. I.e. it uses the ordinary IEEE 802.11a preamble with the 2½ LT symbols construction over 8 µs as first "pilot" symbol, followed by a compatible SIGNAL field, followed by the rest of the orthogonal training symbols.

Two transmit antennas

Figure 2 shows the new solution graphically. The fields shown are according to the IEEE standards, where ST and LT forms the short and long OFDM training sequences, described in Section 17.3.3 in [1], transmitted at both antennas. The next symbol is the SIGNAL field and is described in Section 17.3.4 in [1], also transmitted simultaneously at both TX antennas. This is followed by the new construction of long OFDM training sequences, with the anti-podal, simultaneous transmission of the LT field at TX1 and TX2.

The training sequence sent out denoted as LT_i^{TXn} where TX*n* indicates the TX antenna and where *i* is the discrete time indicator (i^{th} LT symbol transmitted). Lets assume here that LT is identical to the long training sequence as described in 17.3.3 of [1]. Then the training sequences transmitted at each antenna are:

$$LT_1^{TX1} = LT; \; LT_2^{TX1} = LT$$

$$LT_1^{TX2} = LT; \; LT_2^{TX2} = -LT$$

Let the i^{th} set of received LT symbols for a receiver m be called LT_i^{RXm}. The LT related to TX antenna TXn and RX antenna RXm, called LT_n^m, is obtained by adding up and by subtracting respectively for n is 1 and 2:

$$LT_1^m = (LT_1^{RXm} + LT_2^{RXm})/2$$

$$LT_2^m = (LT_1^{RXm} - LT_2^{RXm})/2$$

From the symbol LT_n^m, the channel coefficients can be estimated in a similar way as done in an 802.11a/g system.

Extension to *N* TX antennas

This approach can be made more general for a system with N TX antennas and M RX antennas. Figure 4 shows a schematical representation of this preamble. Using the same notation as for the 2xM system the transmitted preamble is given by:

$$
\begin{array}{llll}
LT_1^{TX1} = LT; & LT_2^{TX1} = LT; & \ldots; & LT_N^{TX1} = LT, \\
LT_1^{TX2} = LT; & LT_2^{TX2} = \exp(j^*(2\pi/N)^*2^*1)^*LT; & \ldots; & LT_N^{TX2} = \exp(j^*(2\pi/N)^*2^*(N-1))^*LT \\
\vdots; & \vdots; & \ldots; & \vdots \\
LT_1^{TXN} = LT; & LT_2^{TXN} = \exp(j^*(2\pi/N)^*N^*1)^*LT; & \ldots; & LT_N^{TXN} = \exp(j^*(2\pi/N)^*N^*(N-1))^*LT
\end{array}
$$

Let the i^{th} set of received LT symbols for a receiver m be called LT_i^{RXm}. The LT related to TX antenna TXn and RX antenna RXm, called LT_n^m, is obtained by:

$$
\begin{array}{llll}
LT_1^m = (LT_1^{RXm} + & LT_2^{RXm} & +\ldots+ & LT_N^{RXm})/N \\
LT_2^m = (LT_1^{RXm} + & \exp(j^*(2\pi/N)^*2^*1)^* LT_2^{RXm} & +\ldots+ & \exp(j^*(2\pi/N)^*2^*(N-1))^* LT_N^{RXm})/N \\
\vdots \;\; = & \vdots & +\ldots+ & \vdots \\
LT_N^m = (LT_1^{RXm} + & \exp(j^*(2\pi/N)^*N^*1)^* LT_2^{RXm} & +\ldots+ & \exp(j^*(2\pi/N)^*N^*(N-1))^* LT_N^{RXm})/N
\end{array}
$$

Note that the earlier described 2xM case is a special case of preamble and that, again, the channel coefficients can be estimated, in a similar way as in an 802.11a/g system, using LT_n^m.

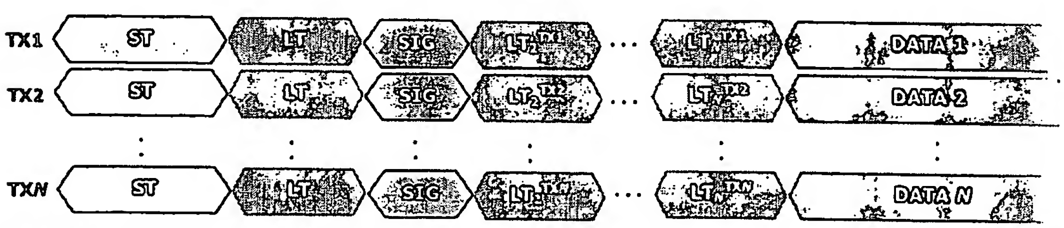


Figure 4 - MIMO preamble for *N* TX branches with time-orthogonal LT symbols, compatibe with legacy devices.

Further enhancements

For TGn MIMO devices it would be helpful to get an early indication of a MIMO transmission. The reserved bit (bit 4) in the SIGNAL field can be used for this purpose. Legacy devices should ignore this bit, TGn devices can set this bit when MIMO is transmitted and reset this bit in legacy modes. Notice that IEEE 802.11a [1] does not specify its value, so legacy devices may set this bit. The MIMO receiver should be aware of that and should be able to return to legacy mode. IEEE 802.11g [2] requires for transmitters to reset this bit to the value "0", but also requires receivers to ignore this bit, so no issue here.

If the number of TX antennas in MIMO mode can dynamically vary within a service area (BSS or IBSS), and it is not determined by the AP to 1 or N (per Beacon), it would be vary helpful for the PHY to have an early indication of the number of antennas. A solution to this would be a field after the SIGNAL field that indicates the number of TX antennas and the number of LT fields that follow. This could possibly be transmitted in

legacy 6 Mbps mode. Further it could contain information like various coding schemes, channel bonding options and LT format.

Figure 5 shows the MIMO preamble with this construction for 2 TX antennas, where NTX is field for Number of TX antennas. This idea is also presented in [3].

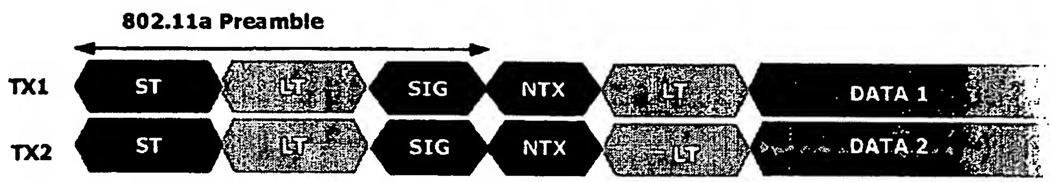


Figure 5 - MIMO preamble with additional NTX field, compatibe with legacy devices.

A drawback of the proposed scheme is the large overhead, i.e. the relatively long training compared to the payload. Notice that for a fixed maximum packet size, the DATA part becomes shorter with MIMO while the training gets proportionally longer. Hence the ratio gets worse quadratically. A solution to prevent this is using shorter LT fields. Normal LT fields have a GI and two LT symbols, a total of 8 μs. Although performance will be better with the same double LT symbols for MIMO training, it would be sufficient to have a single LT symbol. Furthermore and optionally a smaller GI can be applied, e.g. the GI for normal OFDM symbols being 0.8 μs instead of 1.6 μs. Both features may be optional and be indicated in the NTX as described above.

References, that are incorporated by reference herein.

[1] IEEE Std 802.11a; *High-speed Physical Layer in the 5 GHz band*; 1999.

[2] IEEE Std 802.11g/D8.2; *Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band;* Draft version; April 2003.

[3] Jan Boer, Bas Driesen and Pieter-Paul Giesberts, "Backwards compatibility, How to make a MIMO-OFDM system backwards compatible and coexistence with 11a/g at the link level", contribution to the IEEE 802.11 standarisation (IEEE 802.11-03/714r0), Sept. 2003.

[4] U.S.patent application serial no. 60/483,719, attorney docket no. Boer 7-3-2-3, filed on 30 June 2003.

[5] A.R. Dias, S. Rouquette and K. Gosse; *MTMR Channel Estimation and Pilot Design in the Context of Space-Time Block Coded OFDM-Based WLANs*; IST FITNESS.

Backwards compatibility

How to make a MIMO-OFDM system backwards compatible and coexistence with 11a/g at the link level.

Jan Boer, Bas Driesen and Pieter-Paul Giesberts, Agere Systems

The PAR

Some of the modes of operation defined in the HT amendment shall be backwards compatible and interoperable with 802.11a and/or 802.11g.

Meaning for MIMO-OFDM

- Any higher order MIMO-OFDM system (with n Rx antennas) can receive a signal from a lower order MIMO/SISO transmitter (< n Tx antennas, SISO = 11a or 11g)
  - Detection of preamble, interpretation of the header:
    - Determining the number of transmit antennas (number of data streams) and switch Rx accordingly
- Any higher order MIMO-OFDM transmitter (n Tx antennas) can transmit a signal that a lower order MIMO/SISO receiver can receive
  - Switch back to (ultimately) 11a or 11g

* order of MIMO system is dependent on # Tx antennas

Coexistence requirement

Any lower order system (with n Rx antennas) that cannot receive data of a transmitter (with more than n antennas) defers while this transmitter is sending, because it is capable to detect the start of this transmission and retrieve the length (duration) of this transmission.

- Defer not on power only
- Detection of the preamble and interpretation of the length field,
- Using existing multirate capabilities of the current standard(s)

Backward Compatible Preambles

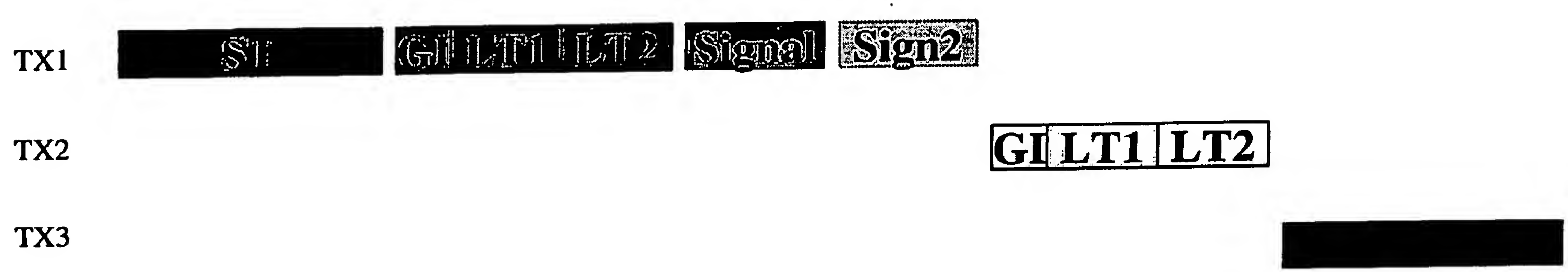
11a/g preamble structure must be maintained

Two examples are given of preamble structures that can be made backward compatible and coexistent:

- Repetition preamble
- Diagonally loaded preamble

3rd way: use protection mechanisms as defined in 11g

1. Repeating preamble



- 802.11a Long Training Symbols (including Guard Interval) repeated on every transmit antenna, separated in time
- Channel training length equal to n times length 802.11a training
- Following is an example for 3 antenna MIMO Tx:

3x3 Mimo Rx vs 11a Rx training

TX1

3x3 Mimo
- Detects short training symbols
- Channel estimation (3 paths), etc

- 11a
  - Detects short training symbols
  - Channel estimation

MIMO notification

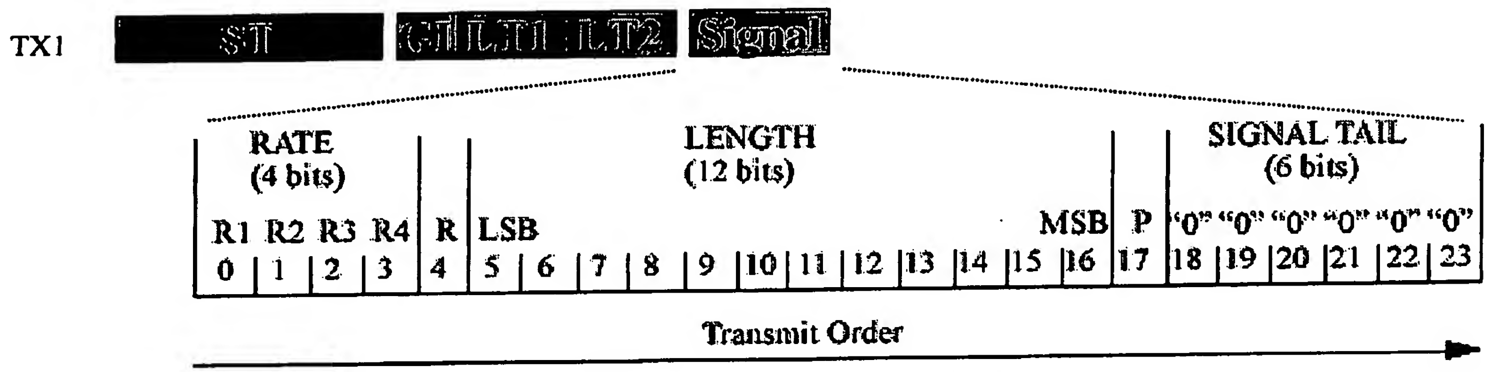


Figure 111—SIGNAL field bit assignment

The Reserved bit 4 in the signal field is used to signal a MIMO transmission (R=1?)

- 11a-1999 standard says:

  Bit 4 shall be reserved for future use

  - The 802.11a standard does not prescribe the value (all other reserved bits shall be set to zero for 11a compliance)
  - This most probably means that R is ignored by a 11a/g implementation

Rate and Length field

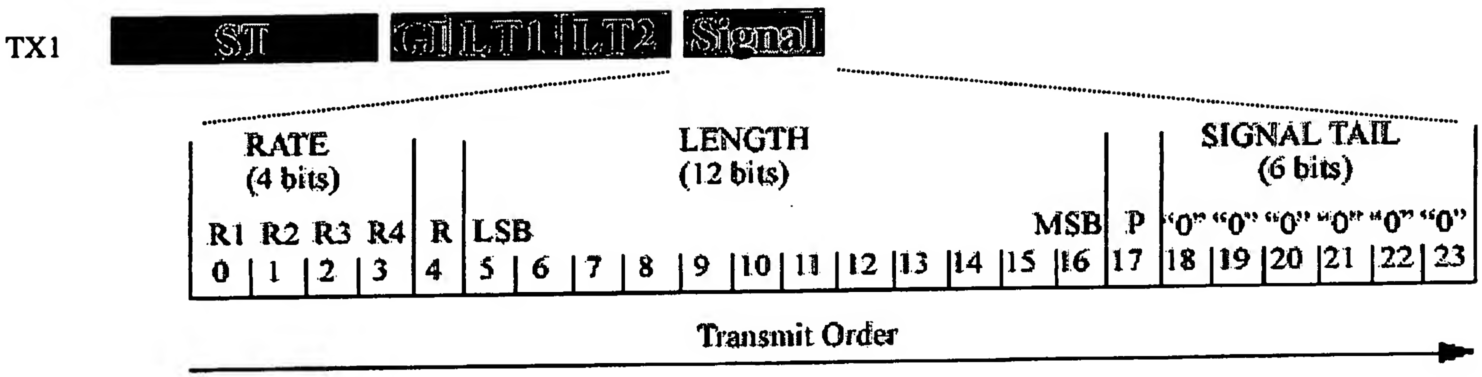


Figure 111—SIGNAL field bit assignment

- Rate: as defined in 11a (6,9,12….54Mbit/s) **per antenna**

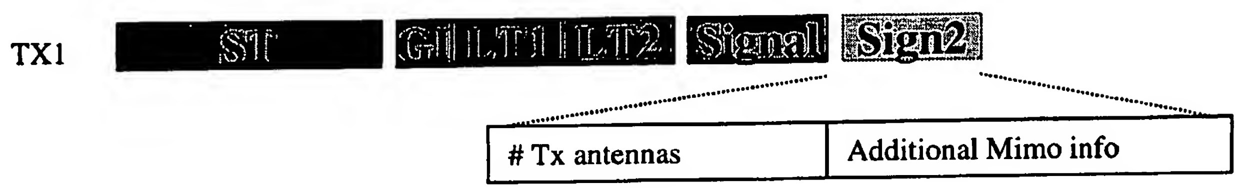
  Length in Bytes as defined in 11a **per antenna**
  - Includes
    - Payload
    - Sign2 (see next)
    - Additional training symbols
    - Padding bits

3x3 Mimo Rx vs 11a Rx signal

Mimo
- Signal detection
  - Rate valid
  - Length valid
- Knows duration
- Mimo notification

- 11a
  - Signal detection
    - Rate valid
    - Length valid
  - Knows duration
  - Ignores R4

3x3 Mimo Rx vs 11a Rx sign2

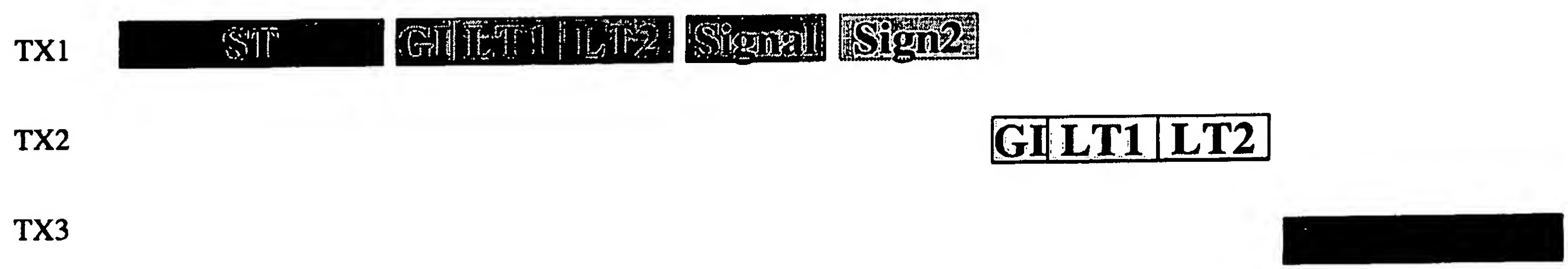


Mimo

- Detects # Tx antennas
- Additional Mimo info:
  - E.g. correction on # bytes per antenna

- 11a
  - Tries to demodulate payload
  - Does not recognize service field
  - Starts to decrement lengthfield

3x3 Mimo Rx vs 11a Rx



Mimo
- Trains other paths
- Starts demod Mimo signal

- 11a
  - Decrements length
  - Defers during duration of mimo transmission (CCA busy)

Repeating preamble

Backwards compatibility and coexistence

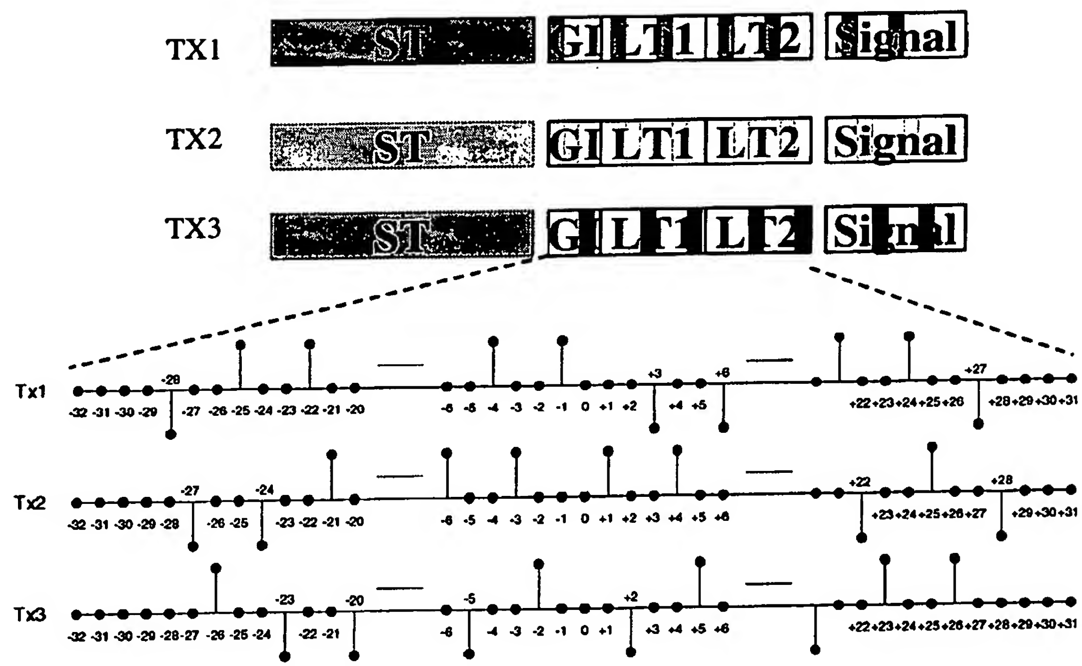
Higher order mimo can switch back to lower order using less antennas and adapt the training accordingly

Lower order mimo can be received by higher order

- Mimo notification + # of transmit antennas

Lower order defers based on length and rate interpretation

2. Diagonally loaded preamble



802.11a Training sequence made orthogonal by diagonally loading subcarriers onto the transmit antennas

- Training length equal to 802.11a training length

Mimo channel estimation

Mimo:

- Step 1: Adding the long training sequences to gain in SNR
- Step 2: Transformation to frequency domain
- Step 3:Demodulation of the combined long training sequences
- Step 4: Interpolation of the subcarriers, to get the full channel estimate:

  - Problem of the edge subcarriers
    - Interpolation of the outer subcarriers cannot be done because these subcarriers have subcarriers only at one side
    - These subcarriers can only extrapolated
    - Extrapolation error is bigger than interpolation error
  - Solution
    - Adding extra subcarriers at the edges of the spectrum
    - These carriers can be used to transfer information

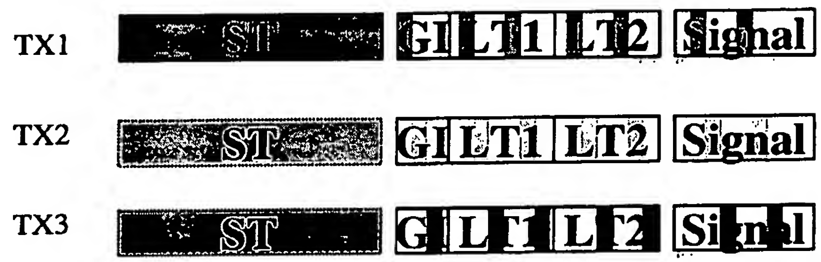
11a/g channel estimation on diagonally loaded preamble

Combination of diagonally loaded sequences is 11a preamble, on which 11a can train.

Different Tx antennas will be reflected in the channel estimation.

- Averaging techniques over carriers in frequency domain or reducing the channel impulse response length in the time domain might disrupt the estimation: possible compatibility issue.

Mimo notification, Length, Rate



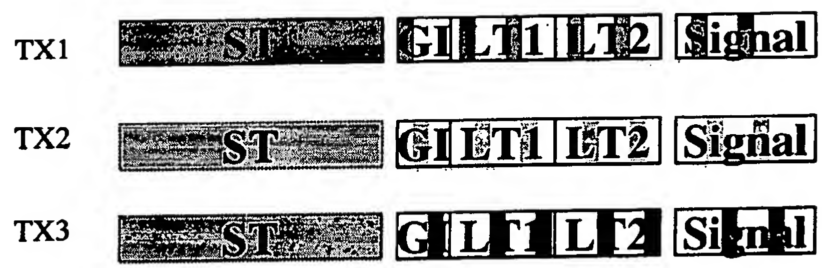
Use R4 in signal field for MIMO notification

- Rate as defined in 11a **per antenna**

Length in Bytes **per antenna**

Extra subcarriers at edge of spectrum can signal the number of transmit antennas

Mimo vs 11a/g reception



Mimo

- Detect short training symbols
- Channel estimation
- Signal detection, rate, length
- # antennas in edge subcarriers
- Decode mimo signal

- 11a/g
  - Detect short training symbols
  - Channel estimation
  - Signal detection, valid rate, valid length
  - Tries to demodulate, no service field
  - Decrements length
  - Defers during duration of mimo transmission (CCA busy)

Diagonally loaded preamble
Backwards compatibility and coexistence

Higher order mimo can switch back to lower order using less antennas and adapt the training accordingly

Lower order mimo can be received by higher order

- Mimo notification + # of transmit antennas

- Lower order defers based on length and rate interpretation

3. Protection Mechanism

As in 11g:

- Precede Mimo transmission with 11a or 11g (RTS/)CTS to reserve medium

Advantage: Mimo preamble can be dedicated

Disadvantage: overhead

Preamble and throughput

Longer preamble effects throughput negatively

If longer preambles are necessary (performance, backwards compatibility,…) the effect on throughput should be clear.

- Next slides show examples of preamble overhead compared to other overheads for 54Mbit/s and 162Mbit/s

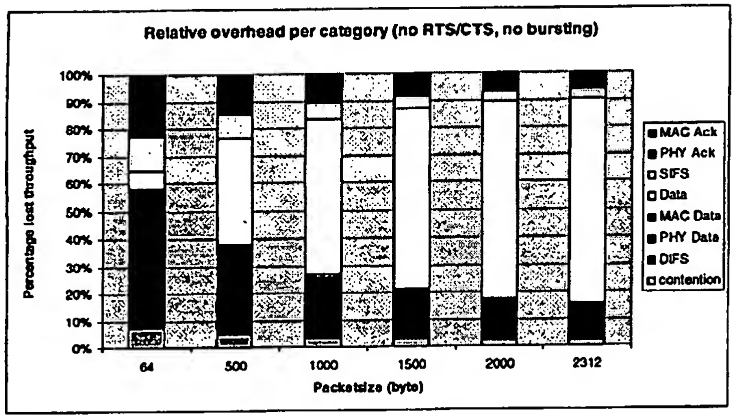
Throughput overview

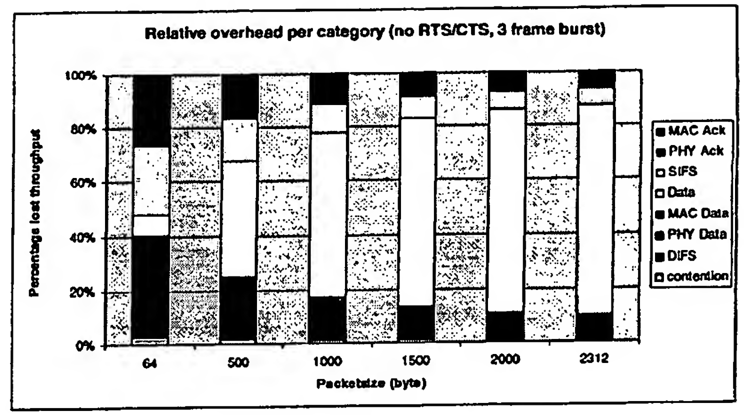
@1500 bytes frames

Efficiency & throughput	Regular	3 frame burst	3 frame aggregation
54 Mbit/s	66% = 36 Mbit/s	69% = 38 Mbit/s	84% = 45 Mbit/s
162 Mbit/s (20µs preamble)	40% = 67 Mbit/s	45% = 75 Mbit/s	66% = 107 Mbit/s
162 Mbit/s (40µs preamble)	35 % = 59 Mbit/s	39% = 65 Mbit/s	62% = 101 Mbit/s

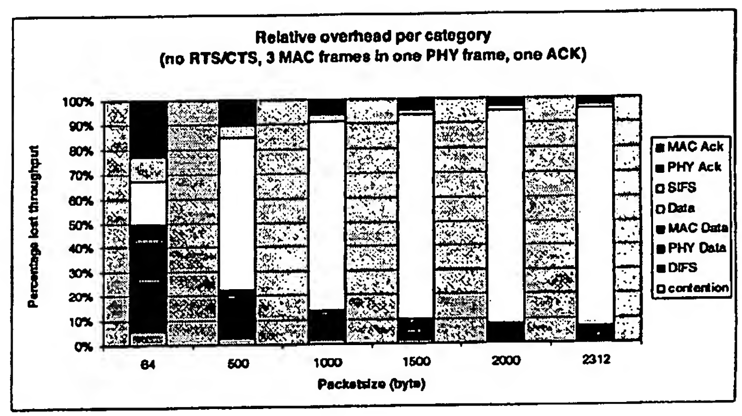
Effect of preamblelength is not neglegable but for the boost of throughput other techniques must be applied such as frame bursting or aggregation

54 Mbit/s



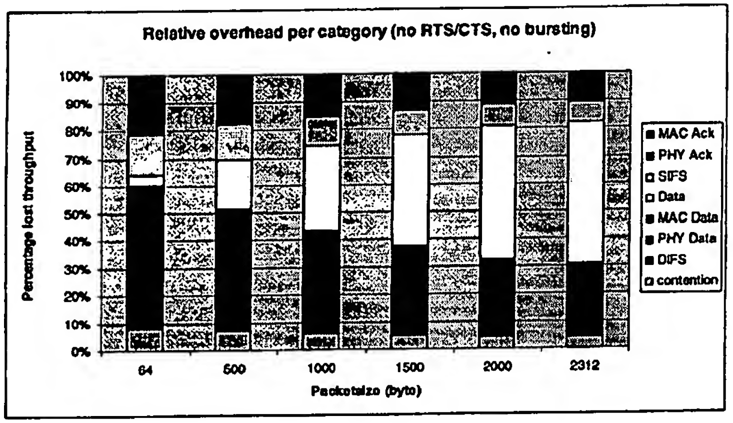


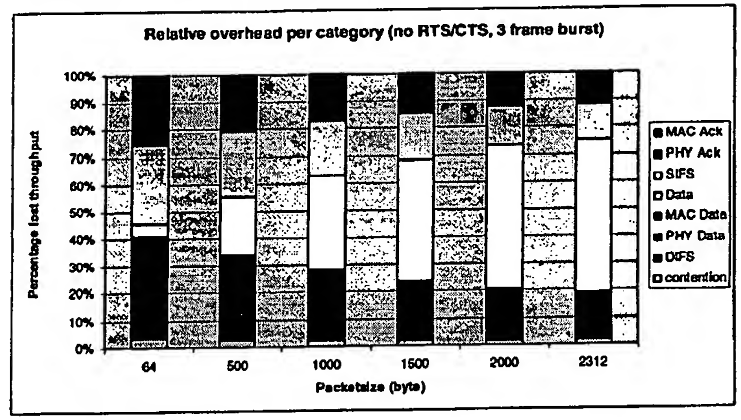
Datarate = 54Mbit/s, Ack rate = 24 Mbit/s



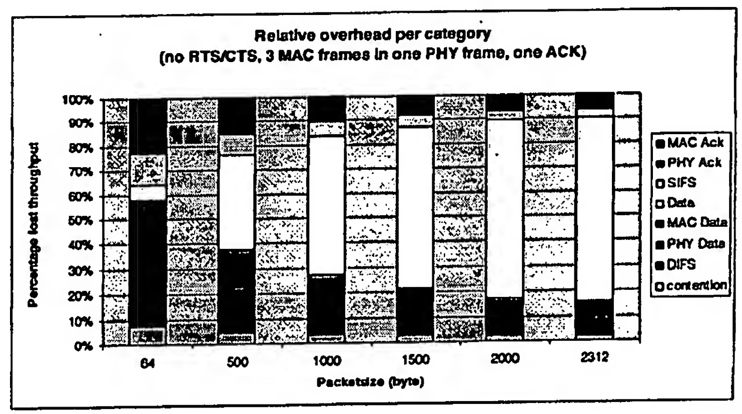
162 Mbit/s

(20 µs preamble+header, diagonally loaded)



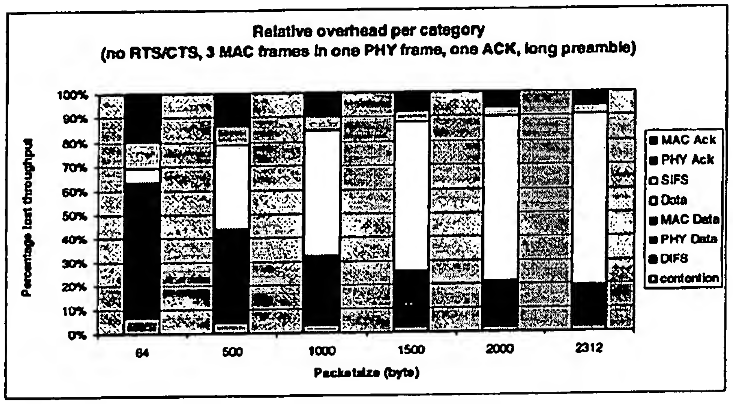


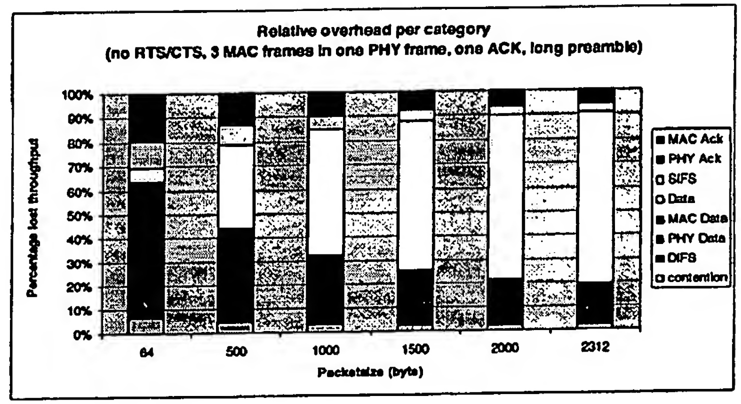
Datarate = 162 Mbit/s,
Ack rate = 54 Mbit/s (both frames on MIMO speed)



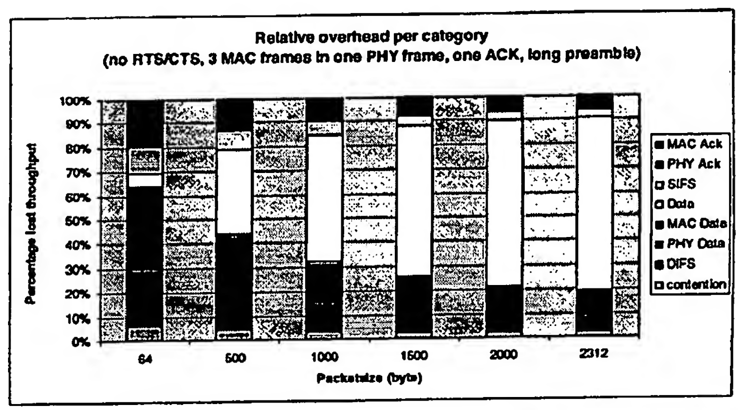
162 Mbit/s

(40 μs preamble+header, repeating)





Datarate = 162 Mbit/s,
Ack rate = 24 Mbit/s (Ack on regular .11a speed)



Conclusion

A MIMO-OFDM system can be made (fairly simple) backwards compatible and coexistent with 11a/g on the link level.

- Preamble based on 11a/g preamble structure
    - Repeated preamble
    - Diagonally loaded preamble
    - 11g protection mechanisms

Criteria for decision:

- Throughput overhead
- Performance
- Complexity

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